# Limits on Lorentz Violation in weak decays

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KKV, *et al,* PLB 729,112 (2014)

# Outline

- Testing Lorentz Violation
- Efforts in weak decays
- Results for non-leptonic Kaon decay
  - Kloe data
  - Theory
  - Theoretical Model
- Conclusion and Outlook

# Testing Lorentz violation

Quantum Gravity

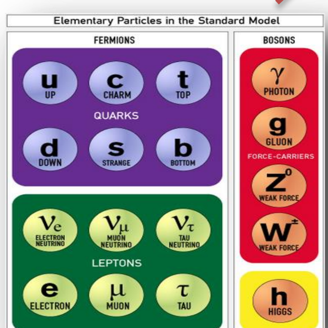
Planck scale

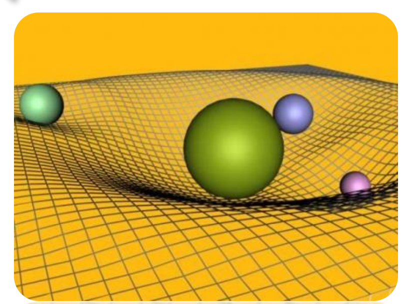
$10^{19}$ GeV

~~CPT~~

O.W. Greenberg, PRL 89, 231602 (2002)

Vacuum expectation values for tensor fields



# Testing Lorentz violation

Quantum Gravity

Planck scale

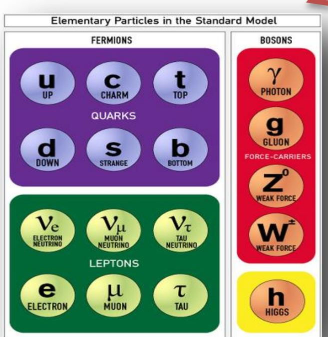
$10^{19}$ GeV

Gauge structure
(Renormalizability)
Energy &momentum conservation
Causality
Spin-statistics

100 GeV

D. Colladay and V.A. Kostelecky, Phys. Rev. D 58, 116002 (1998)

SME

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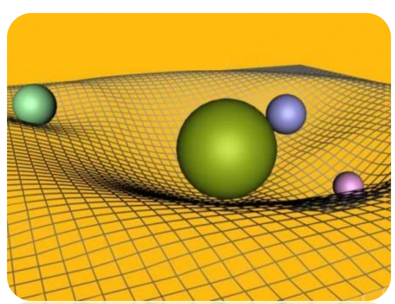

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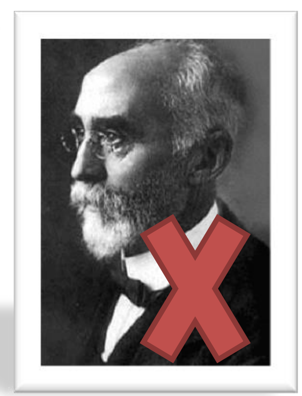
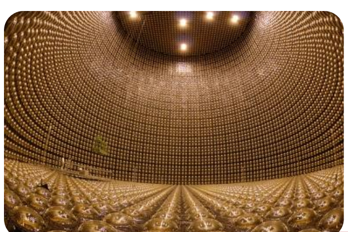


# Testing Lorentz violation

Constrain underlying fundamental theory.

**SME**

Weak sector relatively unexplored!

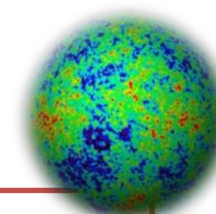


**Muon g-2**
**Neutrino oscillations**
**Matter interferometry**
**Oscillations of K, B, D mesons**
**QED tests in Penning traps**

**Particle-antiparticle comparisons**
**Spectroscopy of hydrogen and antihydrogen**

**Baryon asymmetry**
**Laboratory tests of gravity**
**Clock-comparison measurements**

**High-energy astrophysical observations**
**Tests with microwave cavities and lasers**



**CMB polarization**
**Collider experiments**
**Cosmological birefringence**
**Dispersion from cosmological sources**
**High-energy astrophysical observations**

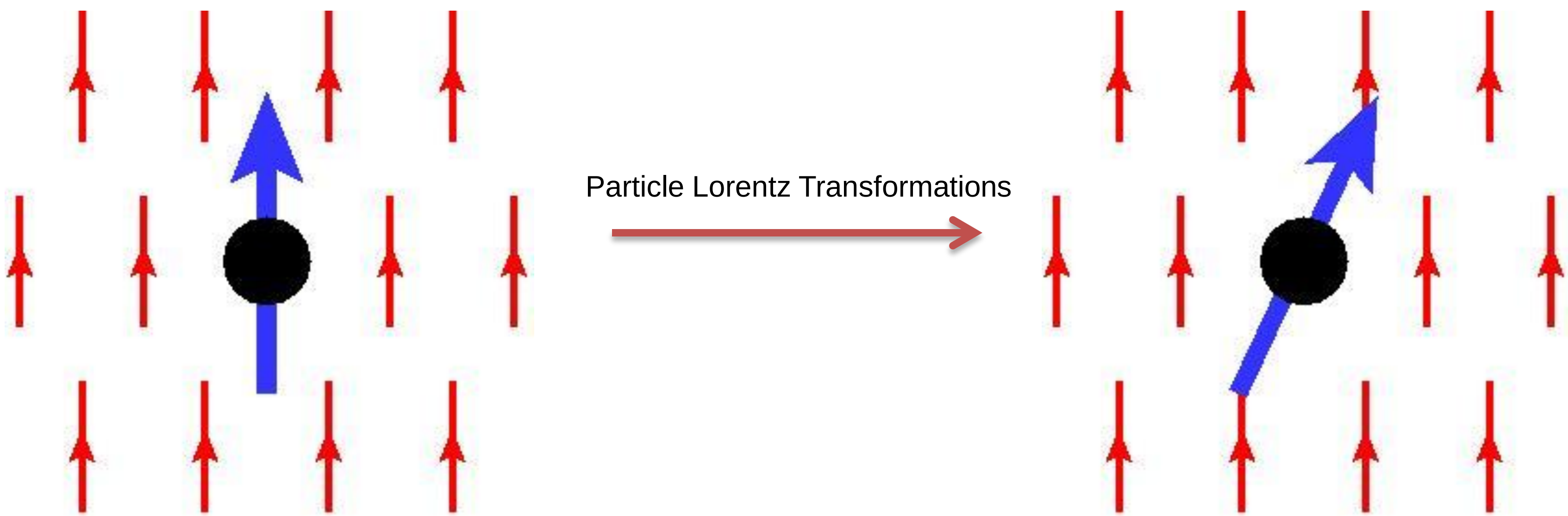
# Testing Lorentz violation

CPT-odd Lorentz violating

$$\mathcal{L} = -\bar{\psi}(m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu)\psi + \frac{i}{2}\bar{\psi}(\gamma_\nu + c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma_5\gamma^\mu)\overleftrightarrow{\partial}^\nu \psi$$

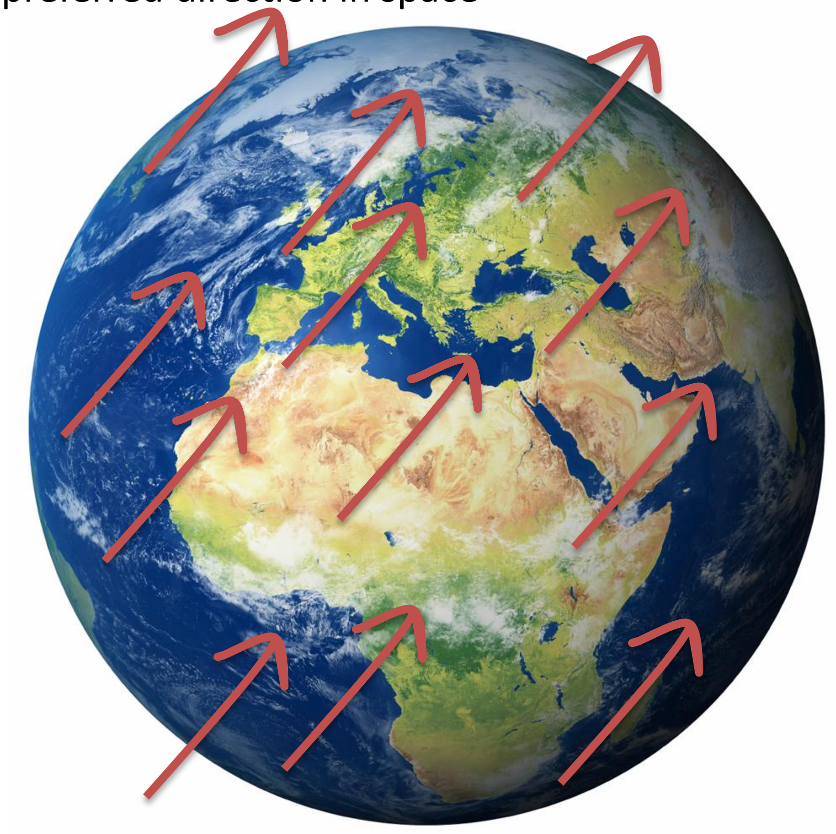
CPT-even Lorentz violating

- ✓ Observer invariance maintained (coordinate independence)
- × Breaking of particle Lorentz transformation (boost or rotations)



# Testing Lorentz violation

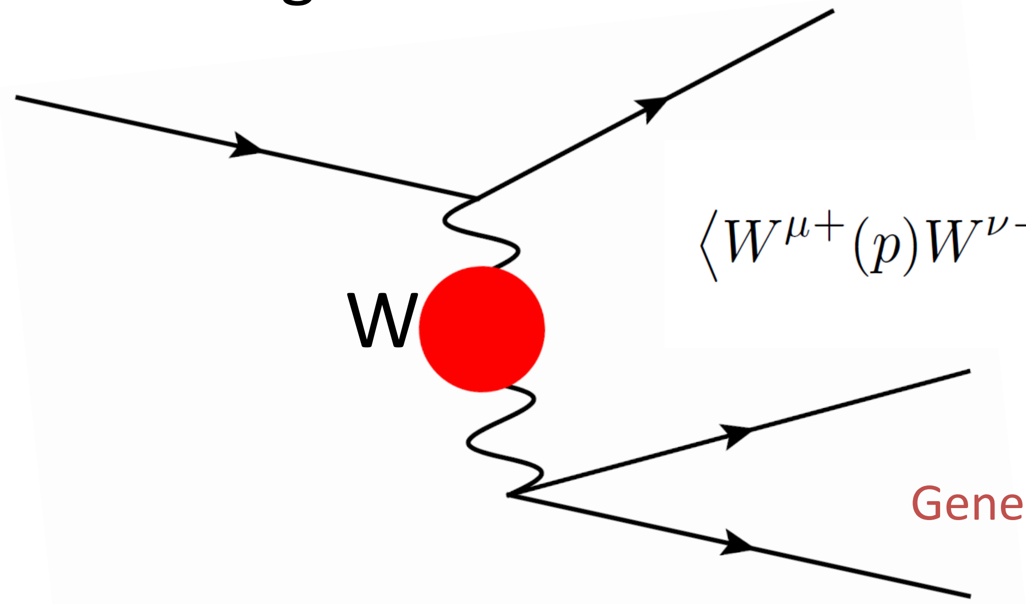
Example: preferred direction in space



- Sidereal variations
- Flip experimental setup

# Testing Lorentz violation

## Testing the Weak interaction




J.P. Noordmans *et al.*, Phys. Rev. C 87, 055502 (2013)

$$\langle W^{\mu+}(p)W^{\nu-}(-p)\rangle = \frac{-i(g^{\mu\nu} + \chi^{\mu\nu})}{M_W^2}$$

General Lorentz violating tensor

For example, in minimal SME,

$$\chi^{\mu\nu} = -k_{\phi\phi}^{\mu\nu} - \frac{i}{2g}k_{\phi W}^{\mu\nu} + \frac{2p_\rho p_\sigma}{M_W^2}k_W^{\rho\mu\sigma\nu}$$

No direct constraints!

# Efforts in weak decays


$\chi$ Allowed β decay at KVI

S.E. Muller *et al.*, Phys. Rev. D 88, R071901 (2013)

stay tuned

$\chi$ Forbidden β decay

reanalysis old experiments

J.P. Noordmans *et al.*, PRL 111, 171601 (2013)

$\chi < 10^{-6}$ -$10^{-8}$

$\chi$ Pion decay at MINOS

B. Altschul, Phys.Rev. D 88, 076015 (2013)

$\chi$ Kaon decay at KLOE

K.K. Vos *et al,* PLB729, 112 (2014)

this talk

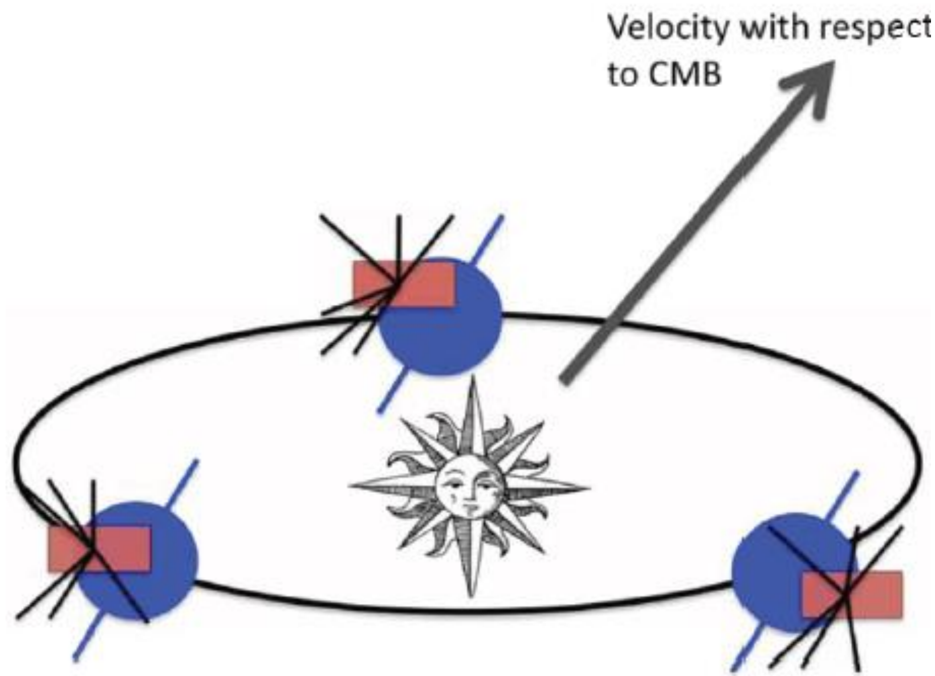
# Directional dependent lifetime asymmetry of neutral Kaons $K^0_S \to \pi^+\pi^-$

parallel

anti-parallel

$$\mathcal{A} = \frac{\tau^+ - \tau^-}{\tau^+ + \tau^-}$$

lifetime



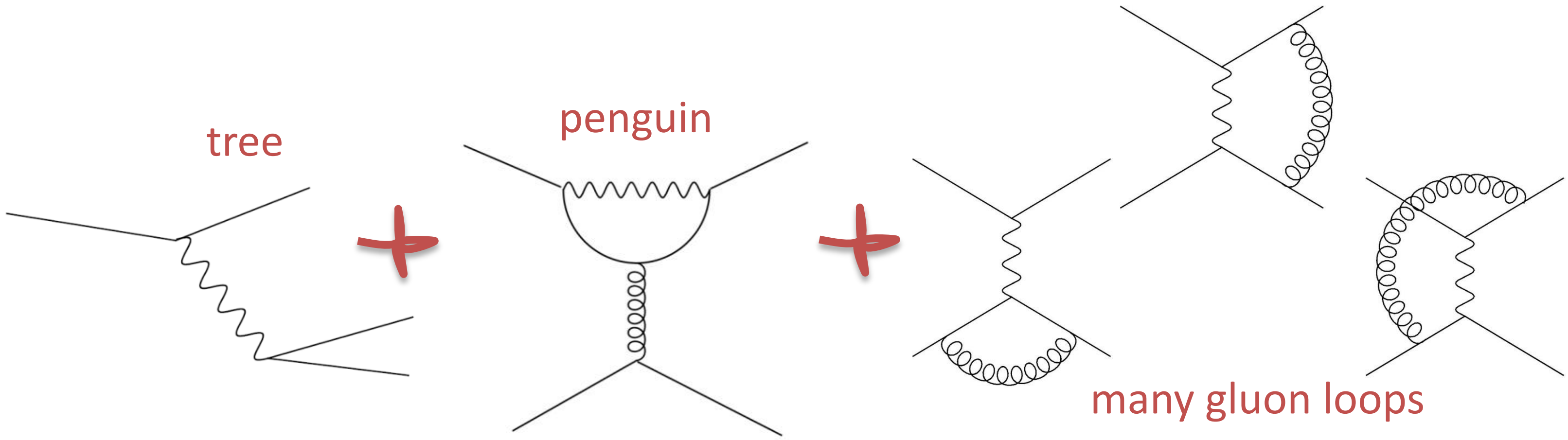

Frame dependent: CMB-dipole frame

| $\{\ell, b\}$ | $\mathcal{A} \times 10^3$ |
|---|---|
| $\mathrm{CMB0} = \{264°, 48°\}$ | $-0.2 \pm 1.0$ [1] |
| $\mathrm{CMB0} = \{264°, 48°\}$ | $-0.13 \pm 0.4$ [2] |
| $\mathrm{CMB1} = \{174°, 0°\}$ | $0.2 \pm 1.0$ [1] |
| $\mathrm{CMB2} = \{264°, -42°\}$ | $0.0 \pm 0.9$ [1] |

[1] F. Ambrosino, Eur. Phys. J. C71, 1604(2011).
[2] A. De Angelis, Nuovo Cim. C034N3, 323 (2011).

# Results: Theory

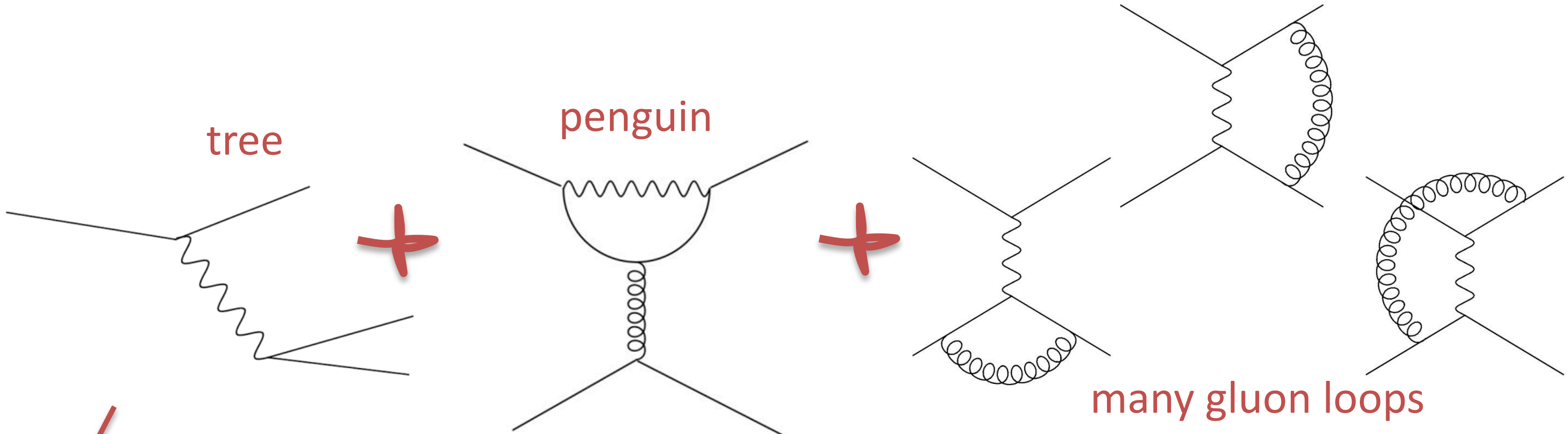
## Non-leptonic decays




Dominant diagrams

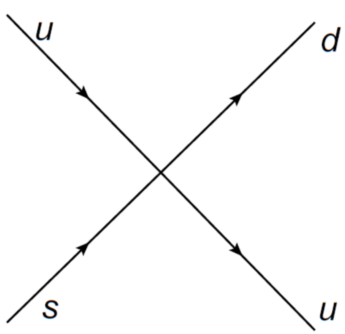
# Results: Theory

## Non-leptonic decays




Dominant diagrams

In the SM



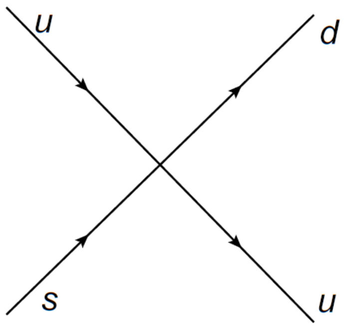

M. Shifman et al, Nucl. Phys. B120, 316(1977)

Effective Hamiltonian ΔS=1 non-leptonic

$$\mathcal{H} \sim \frac{4G_F}{2\sqrt{2}} \cos\theta_C \sin\theta_C \sum_{i=1}^{6} c_i \mathcal{O}_i,$$

# Non-leptonic decays

In the SM

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Effective Hamiltonian ΔS=1 non-leptonic

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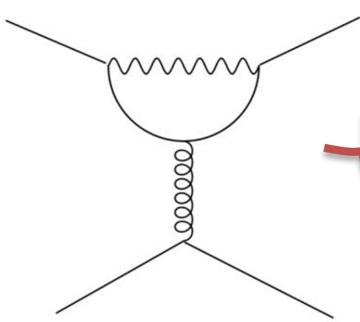
ΔI= ½ rule ?

Lattice QCD

P.A. Boyle *et al.*, PRL 110, 152001(2013)

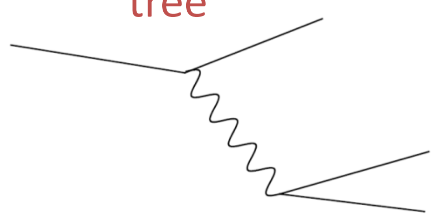
Dominant diagrams



penguin

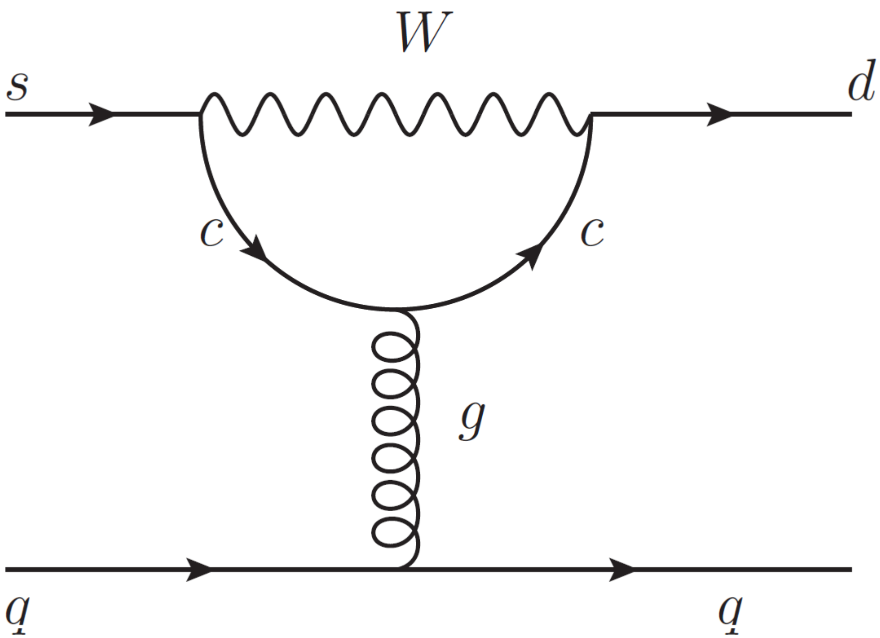
+

tree



# Results: Theoretical model

## Penguin diagram

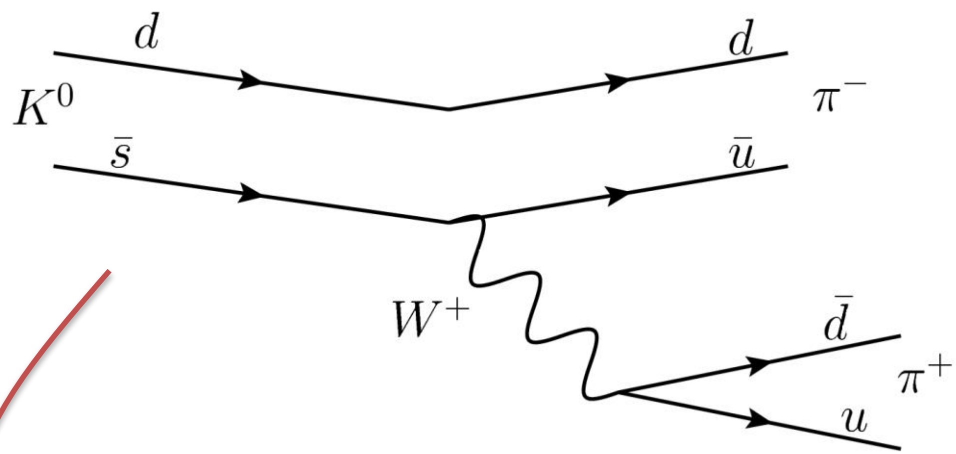



Enhancement due to coupling to right-handed quarks

Cancels in the asymmetry
Assume: tree-level dominant

# Tree-level diagram

Explore possibilities of non-leptonic decays




$$\left\langle \pi^+ | \bar{u}_L \gamma^\mu d_L | 0 \right\rangle (g_{\mu\nu} + \chi^*_{\mu\nu}) \left\langle \pi^- | \bar{s}_L \gamma^\nu u_L | K^0 \right\rangle$$

# Results: Theoretical model

$\mathrm{CMB0} = \{264°, 48°\}$
$\mathrm{CMB1} = \{174°, 0°\}$
$\mathrm{CMB2} = \{264°, -42°\}$

Real & symmetric part

$$\mathcal{A}_{\vec{n}} = -\frac{\frac{4}{3} + \frac{2}{3}\frac{m_\pi^2}{m_K^2}}{(1-\beta_K^2)\left(1-\frac{m_\pi^2}{m_K^2}\right)}(\chi^r_{i0} + \chi^r_{0i})\beta^i_K = -0.343(\chi^r_{i0} + \chi^r_{0i})\,\hat{\beta}^i_K$$

$\gamma^2$ enhancement

Constraints:

$$|\chi^r_{\mathrm{CMB0},0} + \chi^r_{0,\mathrm{CMB0}}| < 2.9 \times 10^{-3} \text{ (95\% C.L.)}$$

$$|\chi^r_{\mathrm{CMB1},0} + \chi^r_{0,\mathrm{CMB1}}| < 6.8 \times 10^{-3} \text{ (95\% C.L.)}$$

$$|\chi^r_{\mathrm{CMB2},0} + \chi^r_{0,\mathrm{CMB2}}| < 5.5 \times 10^{-3} \text{ (95\% C.L.)}$$

# Conclusion & Outlook

- First bounds on Lorentz violation in weak sector.
- Exploratory study in non-leptonic decays.
- Asymmetries get $\gamma^2$ enhancement.

potential for LHCb

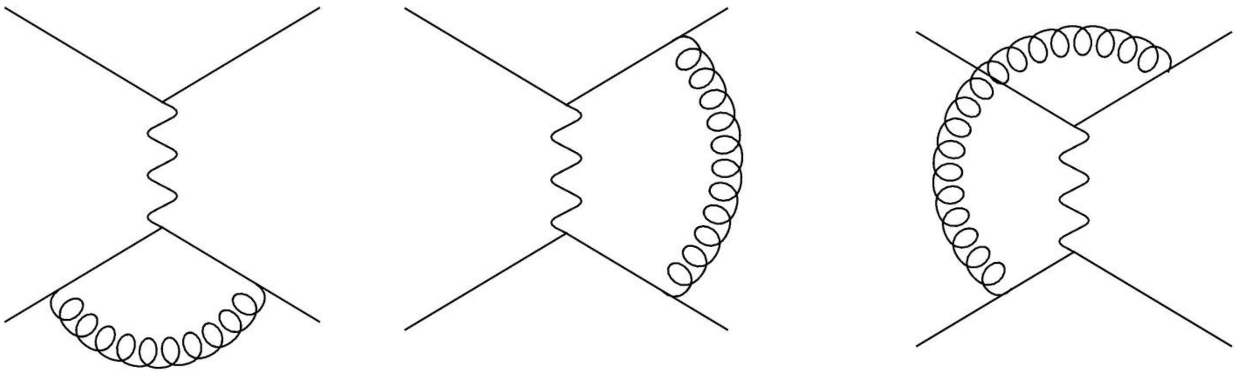
- Semi-leptonic decays theoretical cleaner.

- Other weak decays to test Lorentz Violation

$\mu$ & $\pi$

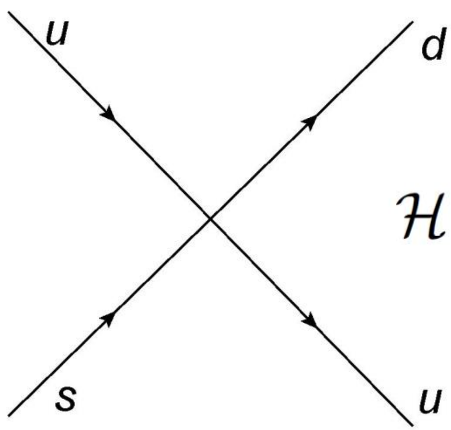
Thank you for your attention

# Results: Penguin Diagram



+ ...

In the SM:

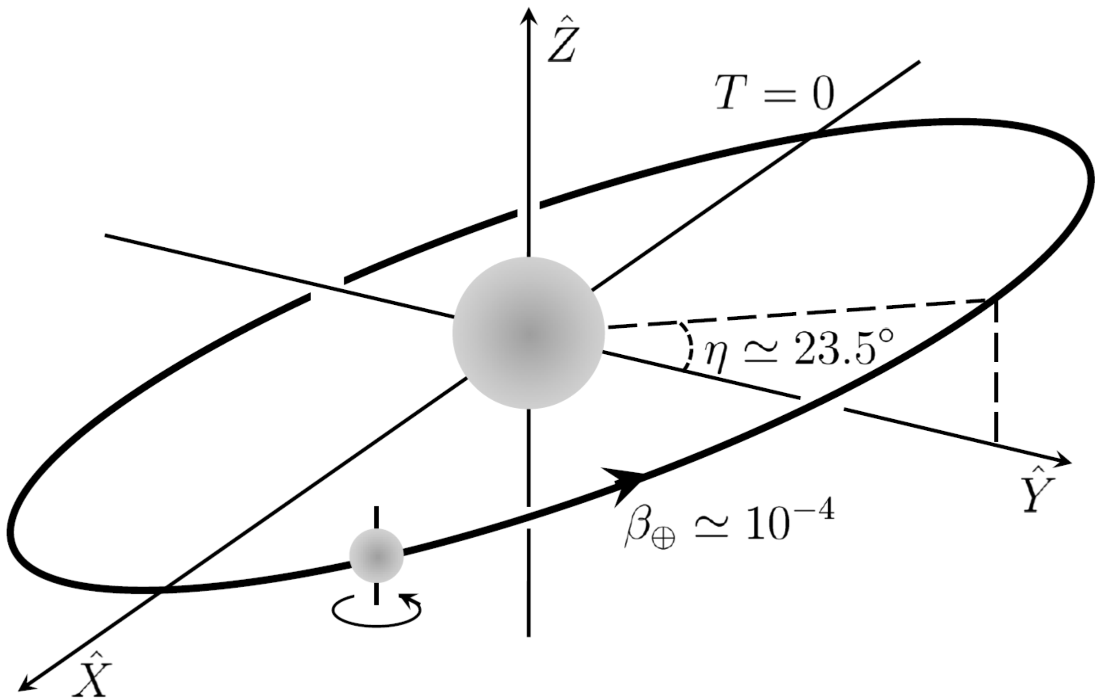



Effective Hamiltonian ΔS=1 non-leptonic

$$\mathcal{H} \sim \frac{4G_F}{2\sqrt{2}} \cos\theta_C \sin\theta_C \sum_{i=1}^{6} c_i \mathcal{O}_i,$$

M. Shifman et al, Nucl. Phys. B120, 316(1977)

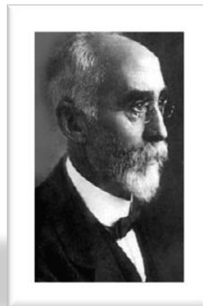
# How to test Lorentz violation?




Sun-centered reference frame

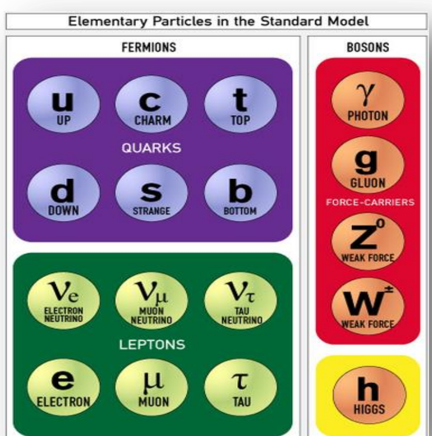
# Testing Lorentz violation

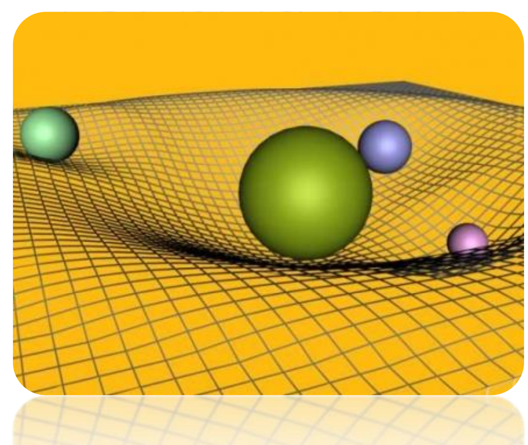
Lorentz
invariance



CPT

Charge conjugation
Parity
Time-reversal



| $\chi_{\mu\nu}$ | Decay | Experiment |
|---|---|---|
| $\chi^{lk}_{r,S} < 10^{-7}$ | Forbidden $\beta$-decay | Newman |
| $\tilde{\chi}^{l}_{i} < 10^{-3}$ | Allowed $\beta$-decay | KVI Groningen |
| $\chi^{0l}_{r,S} < 10^{-3}$ | $K_S$ tree-model | KLOE |

# Status of constraints – slide H.W.

- Assuming contribution of only one element (others are put at zero)
- $|\chi_{rs}^{\mu\nu}| < \begin{bmatrix} 10^{-6} & 10^{-7} & 10^{-6} & 10^{-7} \\ 10^{-7} & 10^{-6} & 10^{-7} & 10^{-6} \\ 10^{-7} & 10^{-6} & 10^{-7} & 10^{-6} \\ 10^{-8} & 10^{-6} & 10^{-8} & 10^{-6} \end{bmatrix}$ and $|\chi_{ia}^{\mu\nu}| < \begin{bmatrix} \times & - & - & - \\ - & \times & 10^{-8} & 10^{-7} \\ - & 10^{-8} & \times & 10^{-7} \\ - & 10^{-7} & 10^{-7} & \times \end{bmatrix}$
- All elements free (cancellations may occur)
- $|\chi_{rs}^{\mu\nu}| < \begin{bmatrix} 10^{-5} & 10^{-4} & 10^{-4} & 10^{-2} \\ 10^{-4} & - & 10^{-6} & 10^{-6} \\ 10^{-4} & 10^{-6} & - & 10^{-6} \\ 10^{-2} & 10^{-6} & 10^{-6} & 10^{-5} \end{bmatrix}$ and $|\chi_{ia}^{\mu\nu}| < \begin{bmatrix} \times & - & - & - \\ - & \times & 10^{-2} & 10^{-2} \\ - & 10^{-2} & \times & 10^{-3} \\ - & 10^{-2} & 10^{-3} & \times \end{bmatrix}$

Forbidden β decay, this experiment, Kaon decay (penguin factor)

- Connection with SM extensions parameters (Kostelecky) (CPT even)

$$\chi_{rs}^{\mu\nu} = -\left(k_{\phi\phi}^{S}\right)^{\mu\nu} \text{ and } \chi_{ia}^{\mu\nu} = -\left(k_{\phi\phi}^{A}\right)^{\mu\nu} - k_{\phi W}^{\mu\nu}/2g$$